PROCEEDINGS OF SCIENCE

High-energy neutrino emissions from the vicinity of supermassive black holes

Shigeo S. Kimura[a,*]

[a] *Frontier Research Institute for Interdisciplinary Science, Tohoku University, 6-3, Aramaki Aza-Aoba, Aoba, Sendai, Japan*

E-mail: shigeo@astr.tohoku.ac.jp

We discuss neutrino production in accretion flows onto supermassive black holes. First, we consider accretion flows in active galactic nuclei (AGN). Luminous and low-luminosity AGN have hot coronae and radiatively inefficient accretion flows (RIAFs), respectively, where cosmic-ray protons can be accelerated by stochastic turbulence acceleration. These cosmic rays produce TeV - PeV neutrinos via interaction with ambient matter and photons. Our scenario can explain cosmic TeV–PeV neutrino and keV–MeV photon backgrounds without contradicting cosmic GeV–TeV photon background. Future neutrino observations will provide a solid test to our scenario. We also apply this scenario to tidal disruption events (TDEs), and our hot corona model could be consistent with the neutrino events reported as the associations with nearby TDEs. To test TDE-neutrino association, deep and wide optical follow-up observations are important, which can be done by near-future optical astronomical facilities.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)1490

1. Source candidates of Astrophysical Neutrinos

IceCube has been detecting high-energy astrophysical neutrinos for more than ten years [1]. The main sources of these neutrinos are still unknown. IceCube collaboration reported the neutrino event associated with a flaring blazar, TX 0506+056 [2], but blazars are unlikely to be the main source of astrophysical neutrinos [3]. Recently, IceCube reported the evidence of neutrino signal from a nearby radio-quiet active galactic nuclei (AGN), NGC 1068 [4]. The neutrino flux from this object is much higher than the gamma-ray flux, which indicates that the emission site needs to be a compact region [5]. A plausible emission site is the accretion flow around the black hole [6, 7], although other emission sites, such as accretion shocks and disk winds [8, 9], are also proposed. In addition, two neutrino events are reported to be associated with bright tidal disruption events (TDEs) [10, 11]. The emission site of these neutrinos are controversial. The accretion flows formed after the TDEs can be a candidate of the neutrino emission site. Here, we will review the theory of neutrino production in accretion flows in AGN and TDEs, and discuss strategies to test neutrino emission models.

2. Accretion Flows onto Supermassive Black Holes and Non-thermal Components

Accretion flows onto supermassive black holes can be classified into two regimes [12]: One is magnetically arrested disks (MADs) and the other is standard and normal evolutions (SANEs). MADs have strong and ordered magnetic fields, which is suitable to launch powerful jets [13]. Thus, they are expected to be in radio-loud AGN. On the other hand, SANEs have a weaker and turbulent magnetic fields, and expected to be in radio-quiet AGN. Here, we focus on SANEs, as neutrino emitting AGN and TDEs are likely in the radio-quiet mode.

SANEs can be classified into two sub types. One is an optically thick, geometrically thin accretion disk [14], which is formed when the mass accretion rate, $\dot{M}$, is close to the Eddington accretion rate, $\dot{M}_{\rm Edd} = L_{\rm Edd}/c^2$. In this state, hot coronae that might sandwich the thin disk are responsible for emitting observed X-ray signals by the Comptonization process. These hot coronae are so tenuous that they can produce non-thermal high-energy cosmic rays, which will lead to efficient neutrino production. The other is a hot accretion flow, or radiatively inefficient accretion flows (RIAFs) [15], which is formed for $\dot{M} \lesssim 0.1\dot{M}_{\rm Edd}$. In this state, the bulk of the accretion flow should be collisionless because it consists of hot and tenuous plasma, leading to the non-thermal particle production in the entire accretion flows.

In accretion flows, magnetorotational instability generates strongly turbulent fields [16], which is confirmed by multi-dimensional magnetohydrodynamic (MHD) simulations [17]. Particle-in-Cell (PIC) simulations that mimic the shearing accretion flows are also performed, and these simulations exhibit that non-thermal particles are produced by magnetic reconnection [18]. These non-thermal particles have larger gyration radii and interact with larger-scale turbulence, which accelerates the particles further. This process is also confirmed by PIC simulations [19, 20] and combination of MHD and test-particle simulations [21–23].

3. Neutrino Emission from AGN

We construct a model to calculate neutrino emission from accretion flows of AGN (see [6, 24] for details). The cosmic-ray protons accelerated in the accretion flows interact with ambient protons and photons, leading to efficient production of neutral and charged pions. In addition, they will escape from the system by diffusion or advection processes. Taking into account these processes, the evolution of the distribution function for non-thermal protons, f_p, is given by [25]

$$\frac{\partial f_p}{\partial t} = \frac{1}{E_p^2}\frac{\partial}{\partial E_p}\left(E_p^2 D_{E_p}\frac{\partial f_p}{\partial E_p} + \frac{E_p^3 f_p}{t_{\rm cool}}\right) - \frac{f_p}{t_{\rm esc}}, \quad (1)$$

where E_p is the particle energy, $t_{\rm cool}$ is the cooling time, $t_{\rm esc}$ is the escape time, and D_{E_p} is the diffusion coefficient in energy space. For the escape process, we consider infall to the black hole and the diffusive escape. For the cooling processes, we take into account the pp inelastic collision, photomeson production, Bethe-Heitler, and synchrotron processes.

The charged pions produced via pp and $p\gamma$ interactions decay to neutrinos and electron-positron pairs. The neutrinos escape from the system, but the secondary elecgtron-positron pairs will emit gamma rays. The decay of neutral pions also produce gamma rays. These gamma rays are absorbed by interaction with lower energy photons, which initiate the electromagnetic cascade emission. We solve transport equations for these gamma rays and electron-positron pairs to estimate the escaping gamma-ray spectrum. See [26] for details.

We separately model the physical quantities for the coronae in luminous AGN and the RIAFs in low-luminosity AGN. For the coronae, we have plenty of observational data, and we are able to construct models using the empirical relations. On the other hand, the models for low-luminosity AGN should be constructed based on theory of accretion flows, and we calibrate a few fuzzy parameters using the X-ray data for nearby low-luminosity AGN.

We solve Eq (1) until steady state is reached, and calculate neutrino and gamma-ray spectrum escaping from the system. For luminous AGN, the cosmic-ray acceleration is stopped by the Bethe-Heitler process with the UV photons from optically thick disks, which typically results in the maximum energy of protons $E_{p,\rm cut} \sim 100$ TeV. On the other hand, in RIAFs in low-luminosity AGN, the energy loss processes are so inefficient that the proton acceleration cannot be prevented until $E_p \gtrsim 10$ PeV. Thus, low-luminosity AGN can emit higher energy neutrinos than luminous AGN.

Using the X-ray and H_α luminosity functions [27, 28], we can estimate the contributions of accretion flows to the cosmic high-energy neutrino background intensity. We found that our AGN model can explain the whole energy range of IceCube neutrino signal without overshooting the cosmic gamma-ray background (Fig. 1). In addition, coronae in luminous AGN and RIAFs in low-luminosity AGN provide dominant contributions to cosmic X-ray and MeV gamma-ray backgrounds, respectively. Thus, accretion flows onto supermassive black holes are potential sources to a wide range of cosmic high-energy particles.

Our scenario predicts that NGC 1068 is the brightest source for IceCube among the nearby Seyfert galaxies, because the intrinsic X-ray flux is highest among the AGN located in the northern sky where IceCube has a better sensitivity. The latest IceCube data for NGC 1068 can be also explained by our model, although other emission sites, such as accretion shock and the disk winds,

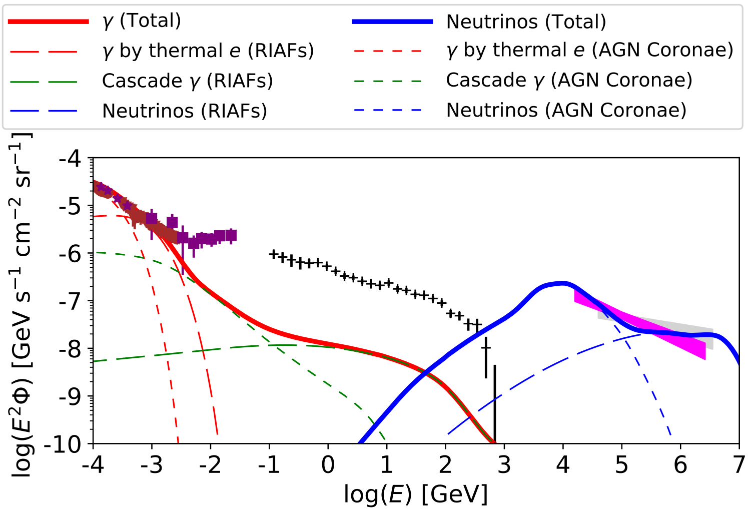

Figure 1: Spectra for cosmic photon and neutrino backgrounds. The red-thick and blue-thick curves are photon and neutrino spectra produced by accretion flows in AGN, respectively. Thin-dotted and thin-dashed lines are contributions by luminous AGN and low-luminosity AGN, respectively. The points and shaded regions are observations for cosmic photon and neutrino backgrounds, respectively. Reproduced from [24] with modification.

can also explain the data [8, 9]. Future neutrino experiments, such as IceCube-Gen2 [29] and KM3NeT [30], will be able to detect neutrino signals from luminous AGN by stacking several nearby sources [31], which will provide a concrete test to our model.

4. Neutrino Emission from TDEs

Two neutrino events, IC191001A and IC200530A, are reported to be associated with bright TDEs, AT2019dsg and AT2019fdr, respectively [10, 11]. AT2019dsg is a luminous TDE, $L_{\rm bol} \sim 3\times10^{44}$ erg s^{-1}, occurred at a relatively nearby galaxy, $z \sim 0.05$ ($d_L \simeq 0.23$ Gpc), while AT2019fdr is a very luminous TDE, $L_{\rm bol} \sim 1\times10^{45}$ erg s^{-1}, occurred at a relatively distant galaxy, $z = 0.267$ ($d_L \sim 1.4$ Gpc). The neutrino detections are delayed to the UV peak time by ~ 150 days for AT2019dsg and ~ 300 days for AT2019fdr. Both events emit weak X-ray and radio signals, and faintness of these emissions ruled out the existence of successful powerful jets.

We apply our accretion flow models to TDE neutrinos [11, 32]. We consider that some fraction of the disrupted stellar material form an accretion disk. The disk is initially in the super-Eddington regime where the plasma is collisional. After the accretion rate becomes lower than the Eddington rate, the accretion disk becomes standard thin accretion disk with hot coronae. The transition timescale from super-Eddington to standard disk regimes can be $\sim 100-300$ days after the peak of the optical lightcurve, which is consistent with the reported time delay. We found that neutrino emission from the coronae can provide a good amount of neutrinos (Fig. 2). The expected number of neutrino-induced events can reach to $\mathcal{N}_\nu \sim 0.1$, although this value requires cosmic-ray pressure

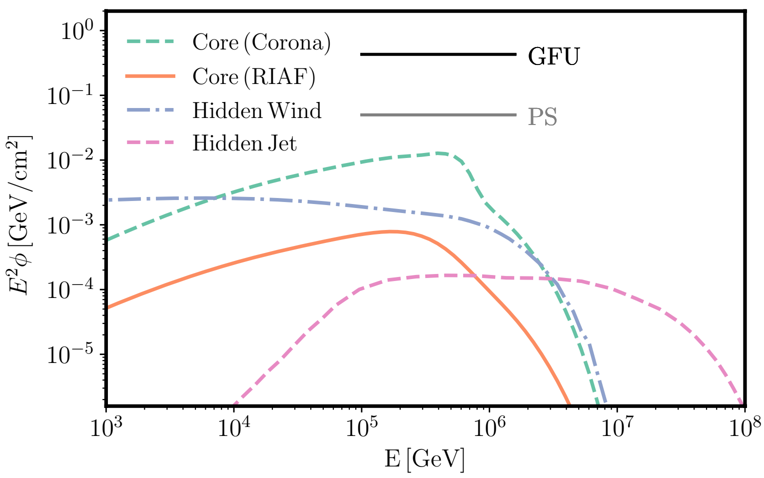

Figure 2: Neutrino spectra from AT2019dsg. The curves are neutrino spectra for various emission models, while the horizontal lines are expected neutrino fluence with Gamma-ray Follow-Up (GFU) and point source (PS) effective areas. The hot corona model can produce neutrinos most efficiently among the models. Reproduced from [32].

comparable to thermal gas pressure. We can also apply our RIAF scenario, but the neutrino fluence is lower than the corona scenario. Thus, RIAF scenario is disfavored. Other scenarios, including outflows [32, 33], MADs in the super-Eddington regime [34], and off-axis jets [35], are also proposed.

In order to test TDEs as neutrino emitter, our team is proposing optical follow-up observations to IceCube neutrino alerts. If the bulk of the cosmic neutrinos are produced by TDEs, the expected distance to a neutrino-emitting TDE should be $z \sim 0.5 - 1$, depending on the redshift evolution of the TDE luminosity function. The peak magnitude of these TDEs at the cosmological distance should be around $\sim 22 - 23$ mag, and it will fade down to $\sim 23 - 25$ mag at the time of neutrino emission. Thus, a wide and deep optical transient search is necessary to identify cosmological TDEs as cosmic neutrino counterparts. The error region of IceCube neutrino events is typically ~ 1 deg. Among current facilities, only Subaru-Hyper Suprime Cam can efficiently detect TDEs happening at cosmological distances. Vera Rubin Observatory will enable us to identify such faint transients near future. Subaru Prime Focus Spectrograph (PFS) will be able to perform spectroscopic follow-up observations to all the transients within the error region of cosmic neutrino events. Thus, combination of Vera Rubin Observatory and Subaru PFS will enable us to confirm whether cosmological TDEs are indeed the neutrino emitter or not.

5. Conclusions

We have discussed the neutrino production in the accretion flows onto supermassive black holes. We considered that hot coronae in luminous AGN and RIAFs in low-luminosity AGN can accelerate cosmic rays via stochastic turbulence acceleration. We constructed models for neutrino production in hot coronae and RIAFs, and found that luminous AGN and low-luminosity AGN efficiently emit 10-100 TeV and 0.1 - 10 PeV neutrinos, respectively. Our model can reproduce the cosmic keV-MeV photon and TeV-PeV neutrino backgrounds without contradicting the cosmic GeV-TeV photon background. Future neutrino experiments will provide a concrete test to our model. We also apply our scenario to TDEs, and found that the neutrino emission from the hot coronae could be consistent with the neutrino-TDE associations. To confirm TDEs as efficient neutrino emitters, deep and wide-field optical followup observations are essential, which can be efficiently done in the era of Vera Rubin Observatory and Subaru PSF.

References

[1] M.G. Aartsen, R. Abbasi, Y. Abdou, M. Ackermann, J. Adams, J.A. Aguilar et al., *First Observation of PeV-Energy Neutrinos with IceCube*, *Physical Review Letters* **111** (2013) 021103 [1304.5356].

[2] IceCube Collaboration collaboration, *Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A*, *Science* **361** (2018) 146 [1807.08816].

[3] IceCube collaboration, *The contribution of Fermi-2LAC blazars to the diffuse TeV-PeV neutrino flux*, *Astrophys. J.* **835** (2017) 45 [1611.03874].

[4] IceCube Collaboration, R. Abbasi, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers et al., *Evidence for neutrino emission from the nearby active galaxy NGC 1068*, *Science* **378** (2022) 538 [2211.09972].

[5] K. Murase, *Hidden Hearts of Neutrino Active Galaxies*, ApJ **941** (2022) L17 [2211.04460].

[6] K. Murase, S.S. Kimura and P. Meszaros, *Hidden Cores of Active Galactic Nuclei as the Origin of Medium-Energy Neutrinos: Critical Tests with the MeV Gamma-Ray Connection*, *Phys. Rev. Lett.* **125** (2020) 011101 [1904.04226].

[7] B. Eichmann, F. Oikonomou, S. Salvatore, R.-J. Dettmar and J.B. Tjus, *Solving the Multimessenger Puzzle of the AGN-starburst Composite Galaxy NGC 1068*, ApJ **939** (2022) 43 [2207.00102].

[8] Y. Inoue, D. Khangulyan and A. Doi, *On the Origin of High-energy Neutrinos from NGC 1068: The Role of Nonthermal Coronal Activity*, ApJ **891** (2020) L33 [1909.02239].

[9] S. Inoue, M. Cerruti, K. Murase and R.-Y. Liu, *High-energy neutrinos and gamma rays from winds and tori in active galactic nuclei*, *arXiv e-prints* (2022) arXiv:2207.02097 [2207.02097].

[10] R. Stein, S. van Velzen, M. Kowalski, A. Franckowiak, S. Gezari, J.C.A. Miller-Jones et al., *A tidal disruption event coincident with a high-energy neutrino*, *Nature Astronomy* **5** (2021) 510 [2005.05340].

[11] S. Reusch, R. Stein, M. Kowalski, S. van Velzen, A. Franckowiak, C. Lunardini et al., *Candidate Tidal Disruption Event AT2019fdr Coincident with a High-Energy Neutrino*, Phys. Rev. Lett. **128** (2022) 221101 [2111.09390].

[12] R. Narayan, A. SÄ dowski, R.F. Penna and A.K. Kulkarni, *GRMHD simulations of magnetized advection-dominated accretion on a non-spinning black hole: role of outflows*, MNRAS **426** (2012) 3241 [1206.1213].

[13] R.D. Blandford and R.L. Znajek, *Electromagnetic extraction of energy from Kerr black holes*, MNRAS **179** (1977) 433.

[14] N.I. Shakura and R.A. Sunyaev, *Black holes in binary systems. Observational appearance.*, A&A **24** (1973) 337.

[15] R. Narayan and I. Yi, *Advection-dominated accretion: A self-similar solution*, ApJ **428** (1994) L13 [astro-ph/9403052].

[16] S.A. Balbus and J.F. Hawley, *A powerful local shear instability in weakly magnetized disks. I - Linear analysis. II - Nonlinear evolution*, ApJ **376** (1991) 214.

[17] M. Machida and R. Matsumoto, *Global Three-dimensional Magnetohydrodynamic Simulations of Black Hole Accretion Disks: X-Ray Flares in the Plunging Region*, ApJ **585** (2003) 429 [astro-ph/0211240].

[18] M. Hoshino, *Angular Momentum Transport and Particle Acceleration During Magnetorotational Instability in a Kinetic Accretion Disk*, *Physical Review Letters* **114** (2015) 061101 [1502.02452].

[19] L. Comisso and L. Sironi, *Particle Acceleration in Relativistic Plasma Turbulence*, Phys. Rev. Lett. **121** (2018) 255101 [1809.01168].

[20] V. Zhdankin, D.A. Uzdensky, G.R. Werner and M.C. Begelman, *System-size Convergence of Nonthermal Particle Acceleration in Relativistic Plasma Turbulence*, ApJ **867** (2018) L18 [1805.08754].

[21] S.S. Kimura, K. Toma, T.K. Suzuki and S.-i. Inutsuka, *Stochastic Particle Acceleration in Turbulence Generated by Magnetorotational Instability*, ApJ **822** (2016) 88 [1602.07773].

[22] S.S. Kimura, K. Tomida and K. Murase, *Acceleration and escape processes of high-energy particles in turbulence inside hot accretion flows*, MNRAS **485** (2019) 163 [1812.03901].

[23] X. Sun and X.-N. Bai, *Particle diffusion and acceleration in magnetorotational instability turbulence*, MNRAS **506** (2021) 1128 [2106.03098].

[24] S.S. Kimura, K. Murase and P. Mészáros, *Soft gamma rays from low accreting supermassive black holes and connection to energetic neutrinos*, *Nature Communications* **12** (2021) 5615 [2005.01934].

[25] S.S. Kimura, K. Murase and K. Toma, *Neutrino and Cosmic-Ray Emission and Cumulative Background from Radiatively Inefficient Accretion Flows in Low-luminosity Active Galactic Nuclei*, ApJ **806** (2015) 159 [1411.3588].

[26] S.S. Kimura, K. Murase and P. Mészáros, *Multimessenger tests of cosmic-ray acceleration in radiatively inefficient accretion flows*, Phys. Rev. D **100** (2019) 083014 [1908.08421].

[27] L. Hao, M.A. Strauss, X. Fan, C.A. Tremonti, D.J. Schlegel, T.M. Heckman et al., *Active Galactic Nuclei in the Sloan Digital Sky Survey. II. Emission-Line Luminosity Function*, AJ **129** (2005) 1795 [astro-ph/0501042].

[28] Y. Ueda, M. Akiyama, G. Hasinger, T. Miyaji and M.G. Watson, *Toward the Standard Population Synthesis Model of the X-Ray Background: Evolution of X-Ray Luminosity and Absorption Functions of Active Galactic Nuclei Including Compton-thick Populations*, ApJ **786** (2014) 104 [1402.1836].

[29] IceCube Gen2 collaboration, *IceCube-Gen2: The Window to the Extreme Universe*, 2008.04323.

[30] S. Adrián-Martínez, M. Ageron, F. Aharonian, S. Aiello, A. Albert, F. Ameli et al., *Letter of intent for KM3NeT 2.0*, *Journal of Physics G Nuclear Physics* **43** (2016) 084001 [1601.07459].

[31] A. Kheirandish, K. Murase and S.S. Kimura, *High-energy Neutrinos from Magnetized Coronae of Active Galactic Nuclei and Prospects for Identification of Seyfert Galaxies and Quasars in Neutrino Telescopes*, ApJ **922** (2021) 45 [2102.04475].

[32] K. Murase, S.S. Kimura, B.T. Zhang, F. Oikonomou and M. Petropoulou, *High-Energy Neutrino and Gamma-Ray Emission from Tidal Disruption Events*, *Astrophys. J.* **902** (2020) 108 [2005.08937].

[33] W. Winter and C. Lunardini, *Interpretation of the Observed Neutrino Emission from Three Tidal Disruption Events*, *Astrophys. J.* **948** (2023) 42 [2205.11538].

[34] K. Hayasaki and R. Yamazaki, *Neutrino Emissions from Tidal Disruption Remnants*, ApJ **886** (2019) 114.

[35] R.-Y. Liu, S.-Q. Xi and X.-Y. Wang, *Neutrino emission from an off-axis jet driven by the tidal disruption event AT2019dsg*, Phys. Rev. D **102** (2020) 083028 [2011.03773].